OPTIMIZATION OF HEAT TREATMENT OF STEEL DEVELOPED FOR TURBINE SHAFTS

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Technology

in

METALLURGICAL AND MATERIALS ENGINEERING

by

AJIT KUMAR KINDO (108MM015)
RAJESH GOEL (108MM022)

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
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National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled, " **Optimization of heat treatment for plain carbon steel used for turbine shafts”** submitted by **Ajit Kumar Kindo (108MM015)**, **Rajesh Goel** (**108MM022**) in partial fulfillment of the requirements for the award of **Bachelor of Technology Degree** in **Metallurgical and Materials Engineering** at National Institute of Technology, Rourkela is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date: 10. 05.2012

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ACKNOWLEDGEMENT

We avail this opportunity to extend our hearty indebtedness to our guide and mentor **Professor Ashok K. Mondal**, Metallurgical & Materials Engineering Department, for his valuable guidance, constant encouragement and kind help at different stages for the execution of this dissertation work.

We also express our sincere gratitude to **Professor B.C. Ray**, Head of the Department, Metallurgical & Materials Engineering, for providing valuable departmental facilities.

We are also grateful to **Mr. Hembram and Ms. Khushboo Dash** for their kind help at various stages of the work and helping understand various things related to the project.

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CONTENTS

ABSTRACT

Turbine shafts are basically used in steam turbine, hydro turbine and wind turbines. These turbine shafts require very stringent properties. Generally high yield strength, tensile strength and percentage elongation are required along with high impact values at the same time. In addition, the material should exhibit good high temperature properties such as creep, elevated temperature strength and thermal stability. Practically the turbine shafts used are very massive in size. Hence, the coefficient of thermal expansion should be small so as to maintain a minimum temperature gradient between the core and the surface of turbine shafts. If the temperature gradient crosses a certain limit, it may lead to generation of crack inside the structure.

As mentioned, we require high tensile properties along with good impact strength for proper application. But it is generally observed that these two properties are inversely related to each other i.e. the efforts to increase the tensile strength of materials results in decrease in impact strength and vice versa. Therefore, one has to judiciously select the heat treatment parameters so as to maintain a good combination of these properties.

Keywords: Turbine shafts, yield strength, impact strength.

LIST OF FIGURES AND TABLES

CHAPTER

ONE

INTRODUCTION

1-1 INTRODUCTION

A shaft is a metal bar- usually cylindrical in shape and solid, but sometimes hollow- that is used to support rotating components or to transmit power or motion by rotary or axial movement [1]. The turbine shaft is generally used to extract energy from a fluid flow and converts it into useful work. These turbine shafts operate under severe conditions such as dust laden or corrosive atmospheres, extreme temperatures, as in gas turbines and even low temperatures, as is arctic or cryogenic environments. In addition, shafts may be subjected to variety of loads- in general, tension, torsion, compression, bending or combination of these and sometimes vibratory stresses [1]. The failure in turbine shafts is generally caused due to metal fatigue. Fatigue failures start at the most vulnerable point in a dynamically stressed area particularly where there is a stress raiser [1].

The need is to look out for a material which can be effectively used for the production of turbine shafts. Plain carbon steel is selected for the present investigation. The steel is specified under the ASTM A668 Class D standard. The steels specified under this standard are plain carbon steel and alloy steel basically forged for turbine shaft application. These materials should exhibit high yield strength and high % elongation along with high toughness values. But it is generally observed that these two properties are inversely related to each other. If we increase the tensile properties then the toughness or impact value decreases and vice-versa. So, one has to judiciously select the heat treatment processes to maintain a good combination of these two properties.

1-2 <u>OBJECTIVE AND SCOPE OF WORK</u>

The objective of this project is to evaluate the best possible heat treatment to get an optimum combination of tensile strength and impact property. The properties though can easily be achieved at a prototype sample, but it is difficult to achieve the same for actual sized applications in actual working conditions. Hence, the scope of the dissertation will include:

- Hardening of the received sample (as-forged and normalized) with oil as the quenching media.
- Tempering of the hardened sample at different temperatures to vary the mechanical properties.
- Extrapolate the obtained values on the prototype for the actual sized applications of turbine rotor.

CHAPTER

TWO

LITERATURE REVIEW

2-1 BACKGROUND

2-1-1 TURBINES

Turbine is a rotating engine that is powered by a working (moving) fluid and the force of its rotation is converted into usable energy. Turbines are the most essential component of many industrial mechanisms. Most of the electrical power on earth is derived from turbines.

Turbines work with the principle that "working (moving)" fluid contains "potential energy". There are basically two classes of turbines, impulse turbines and rotor turbines. Within the two classes of turbines, there are different types of turbines such as steam turbines, wind turbines, gas turbines and contra-rotating tubes (which are paired and rotate in different directions to create more energy efficiency).

Turbines are used essentially in generating electrical energy. Apart from being an autonomous power source turbines also work along with other mechanisms such as jet engines use turbines, internal combustion engines contain gas turbines. A new innovation is tidal turbines, which use the tide's natural rhythms to create energy.

2-1-2 TURBINE SHAFTS

A shaft is a cylindrical rod that connects the turbine to the generator. It rotates at the same speed as the turbine. Either HSMA (High Strength Micro Alloy) steel or a heat treated steel is best suited for the manufacture of the turbine shafts. ASTM A668 Class D standard specify the chemical composition and mechanical properties of heat treated steel required to best suit the turbine shaft application.

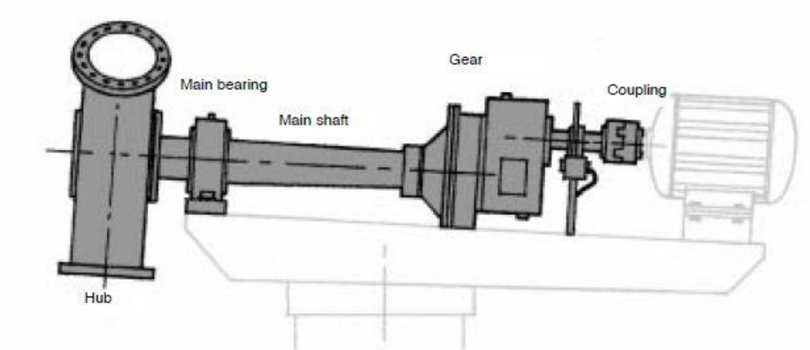

Fig. 2.1 Wind turbine shaft showing link between the wind turbines blades and generator.

2-1-3 FAILURE OF TURBINE SHAFTS

The turbine shafts generally operate at very severe conditions such as dust laden atmospheres, corrosive atmospheres, and high or low temperatures atmospheres. Moreover it is subjected to variety of loads such as tension, torsion, compression, bending, or combination of these and is also subjected to vibratory stresses. Wear by bearing and metal fatigue are the major contributor of shaft failure.

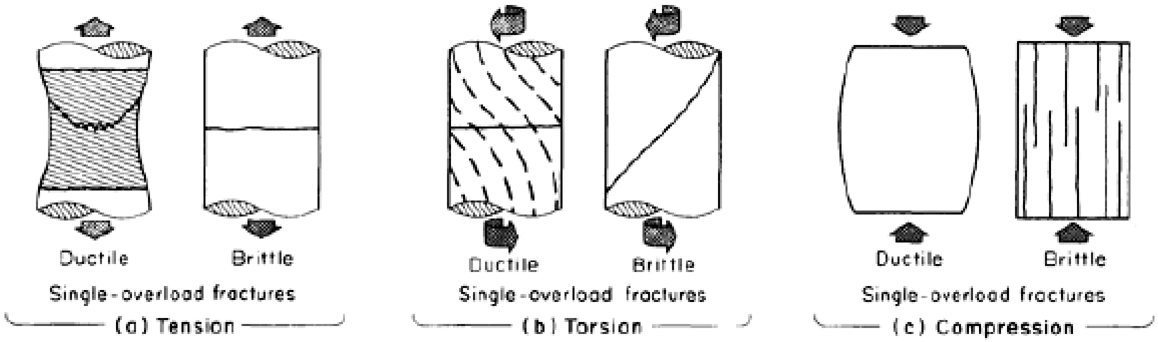

Fig. 2.2 [1] Single over-loaded fracture behavior of materials under (a) Under simple tension, (b) Under torsion, (c) Under compression loading.

Wear of metal parts is commonly classified into either of two categories: abrasive wear or adhesive wear [1]. Generally abrasive wear is caused when the undesired removal of material by a cutting mechanism, can reduce the size and destroy the proper shape of the shaft which then fail by another means such as fracture or may cease to perform its designed function. There are many foreign particles such as sand, dirt and other debris, in the lubricant that can cause wear of shaft.

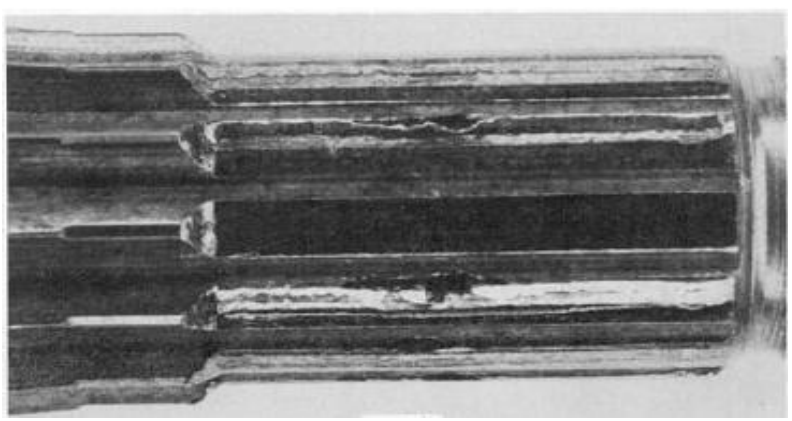

Fig. 2.3 [1] Failure area showing worn splines caused due vibration in presence of sand and metallic particles.

Fatigue in shafts can generally be classified into three basic subdivisions: bending fatigue, torsional fatigue, and axial fatigue [1]. Bending fatigue results from the types of bending loads i.e. unidirectional (one way), reversed (two way) and rotating which cause the stress to alternate between two stresses. The torsional fatigue is caused due to a fluctuating or an alternating twisting moment. Contact fatigue is also a cause to the failure of shafts which occur when components roll, or roll and slide, against each other under high contact pressure and cyclic loading.

2-2 ASTM A668

This specification covers untreated and heat treated carbon and alloy steel forgings are available for specific application such as pressure vessels, railroad use, turbine generators, gearing and other involving special temperature requirements [2].

It consists of different classes from 668/A to 668/N each having different properties as per their respective requirements. All forgings, other than Class A, should be heat treated [2].

The material used in turbine shafts is determined mainly under Class D of this standard and the chemical composition and mechanical properties are specified accordingly.

2-2-1 CHEMICAL COMPOSITION

The ASTM A668 steel material should have the following composition as given in APPENDIX-I.

2-2-2 MECHANICAL PROPERTIES

The tensile properties of ASTM A668 material are given in the APPENDIX-I.

2-3 MECHANICAL WORKING

2-3-1 FORGING

Forging is the working of metals into a useful shape by hammering or pressing [3]. It is generally carried out when the material is in hot condition but sometimes cold forging is also done. The two main classes of equipment used for forging operations are forging hammer and forging press. Forging hammer works with the principle of delivering rapid impact blows to the metal whereas forging press works on the principle of delivering slow speed compressive force.

The two broad categories of forging processes are open-die forging and closed die forging [3]. Open die forging is generally done between two flat dies or dies of simple shape. Closed die forging is generally carried out between two dies i.e. work piece is placed between two die halves and pressure is applied to form a closed cavity thus have the impression of the desired shape.

Some of the forging operations are edging, fullering, drawing, swaging, piercing, punching, upsetting, etc.

2-4 <u>HEAT TREATMENT</u>

2-4-1 HARDENING

Hardening is a heat treatment process in which material is heated to austenitising temperature , soaking at this temperature and then cooling at a rate faster than the critical cooling rate such that martensite is formed.

The main objective of hardening is to induce high hardness the material and impart high wear and abrasion resistance to the material. In pearlitic class of steel hardening is done to induce high strength along with good toughness and ductility.

It is divided into two parts:

1. Austenitising: it involves heating the steel to the austenitising temperature holding at that temperature for soaking.
2. Quenching: it involves fast cooling of the heated material (greater than the critical cooling rate) to room temperature so as to surpass the pearlitic bay.

2-4-2 TEMPERING

It is a heat treatment process which involves heating of a material to a temperature maximum up to the lower critical temperature (A_1 for steel) then cooling at a very slow rate (i.e. air cooling). The temperature of tempering is decided based on the strength and toughness of the material required during the service period.

During tempering generally martensite decomposes and thus results in decrease of strength and hardness thereby causing an increase in toughness (impact strength) and ductility of the material.

The main aim of tempering is to relieve the internal stresses developed during hardening, restore ductility and toughness, improve dimensional stability by decomposition of retained austenite, and improve magnetic property by transforming non-magnetic austenite to magnetic product.

The stages of tempering for plain carbon steel:

1. First stage of tempering (up to 200℃): during this stage precipitation of ε carbide takes place due to decrease in tetragonality of martensite.
2. Second stage of tempering (200 ℃ to 300℃): during this stage decomposition of retained austenite takes place .
3. Third stage of tempering (200℃ to 350℃): during this stage formation of rods or plates of cementite takes place along with complete loss of tetragonality and dislocation of ε carbide.
4. Fourth stage of tempering (350℃ to 700℃): during this process coarsening and spherodisation along with recovery and recrystallization of ferrite.

2-5 SCANNING ELECTRON MICROSCOPE (SEM)

Scanning electron microscopy is basically used for materials characterization process. It operates at 2 to 50 kV; a range of 15 to 25 kV is common for most metallurgical and ceramic applications

[4]. Electromagnetic lenses are present which is used to form a small-diameter electron probe. As the electron beam scans the inside of the CRT screen, likewise a set of scan coils raster the electron probe over the specimen surface. When the electron beam struck the sample at any point then at that point many electron-specimen interactions takes place which produces a number of different measurable signals, such as secondary electrons, back scattered electrons and characteristic x-rays.

The intensity of the emitted signal is a function of the specimen [4]. The intensity of the signal may vary depending upon the surface topography or composition. The signals which produce due to electron-specimen interactions are collected, amplified, and displayed on a CRT. The regions which emit intense signal appear bright whereas the regions which emit weak signals appear dark on the CRT screen. The ultimate image resolution in the scanning electron microscope is of the order of the electron probe diameter.

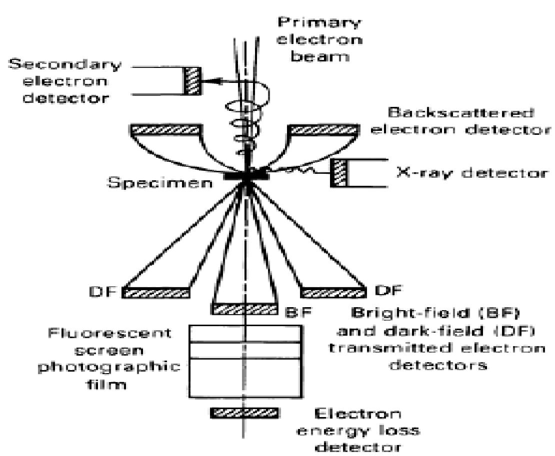

Fig. 2.4 Positioning of the signal detectors in the analytical electron microscope column [4].

2-6 <u>X-RAY DIFFRACTION</u>

About 95% of all solid materials can be described as crystalline. When X-rays interact with a crystalline substance, one gets a diffraction pattern.

In 1919, A.W. Hull gave a paper titled, "A New Method of Chemical Analysis". Here he pointed out that "…every crystalline substance gives a pattern; the same substance always gives the same pattern; and in a mixture of substances each produces its pattern independently of the others. " The X-ray diffraction pattern of a pure substance is, therefore, like a fingerprint of the substance." The powder diffraction method is thus ideally suited for characterization and identification of polycrystalline phases.

The diffraction patterns are generally governed by the following equation, popularly termed as the Bragg's Law:

$$n\lambda = 2d\sin\theta$$

Where *n* is integer, λ is wavelength of incident wave, *d* is spacing between the planes in the lattice, and θ is angle between the incident ray and the scattering planes

2-7 <u>FRACTOGRAPHY</u>

Fractography is defined as the study of the fracture surface after the failure. This provides basic understanding about how the metals fracture and how the environment affects the fracture process. Fracture in engineering alloys can occur by a trans-granular (through the grain) or an intergranular (along the grain boundaries) fracture path [5]. Basically there are four principal fracture modes. They are dimple rupture, cleavage, fatigue, and decohesive rupture.

2-8 TENSILE TESTS

The tension test is one of the most commonly used tests used for evaluating materials. In its simplest form, the tension is accomplished by gripping opposite ends of the test item within the load frame of a test machine [6]. A tensile force is applied by the machine, resulting in gradual elongation and eventual fracture of the test item [6]. The tensile test is done based on ASTM E8/E8M standards.

Some of the terminologies used in the tension test are as follows [7]:-

(i) Discontinuous yielding: - in a uniaxial tension test, it is the fluctuation of force observed at the onset of plastic deformation, due to localized yielding.

(ii) Elongation at fracture: - the elongation measured just prior to the sudden decrease in force associated with fracture.

(iii) Lower yield strength (LYS):- in a uniaxial test, the minimum stress recorded during discontinuous yielding, ignoring transient effects.

(iv) Uniform elongation, (El_u):- the elongation determined at the maximum force sustained by the test piece to necking or fracture, or both.

(v) Upper yield strength (UYS):- in a uniaxial test, the first stress maximum (stress at zero slope) associated with discontinuous yielding at or near the onset of plastic deformation.

(vi) Yield point elongation (YPE):- in a uniaxial test, the strain (expressed in percentage) separating the stress-strain curve's first point of zero slope from the point of transition from discontinuous yielding to uniform strain hardening.

The following fig. 2.5 shows the standard cylindrical specimen for tensile testing. Along with it table 2.1 shows dimensions of the standard cylindrical specimen.

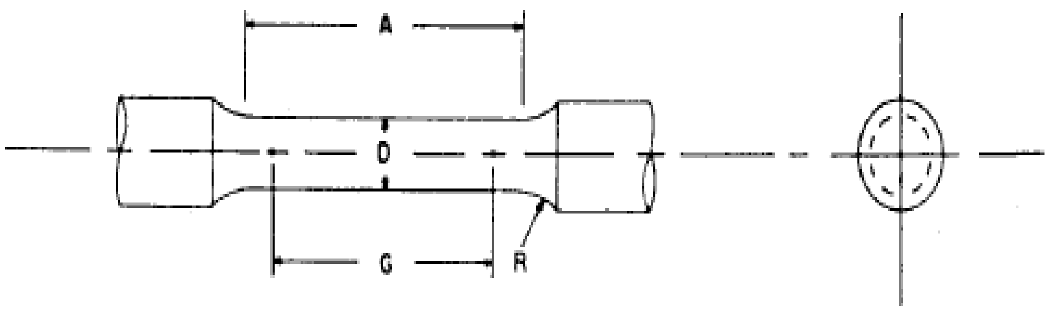

Fig. 2.5 Standard cylindrical tensile specimen [7].

Dimensions, mm [in.] For Test Specimens with Gage Length Four times the Diameter [E8]					
	Standard Specimen	Small-Size Specimens Proportional to Standard			
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
G—Gage length	50.0 ± 0.1 [2.000 ± 0.005]	36.0 ± 0.1 [1.400 ± 0.005]	24.0 ± 0.1 [1.000 ± 0.005]	16.0 ± 0.1 [0.640 ± 0.005]	10.0 ±0.1 [0.450 ± 0.005]
D—Diameter (Note 1)	12.5 ± 0.2 [0.500 ± 0.010]	9.0 ±0.1 [0.350 ± 0.007]	6.0 ± 0.1 [0.250 ± 0.005]	4.0 ± 0.1 [0.160 ± 0.003]	2.5 ± 0.1 [0.113 ± 0.002]
R—Radius of fillet, min	10 [0.375]	8 [0.25]	6 [0.188]	4 [0.156]	2 [0.094]
A—Length of reduced section, min (Note 2)	56 [2.25]	45 [1.75]	30 [1.25]	20 [0.75]	16 [0.625]
Dimensions, mm [in.] For Test Specimens with Gage Length Five times the Diameter [E8M]					
	Standard Specimen	Small-Size Specimens Proportional to Standard			
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
G—Gage length	62.5 ± 0.1 [2.500 ± 0.005]	45.0 ± 0.1 [1.750 ± 0.005]	30.0 ± 0.1 [1.250 ± 0.005]	20.0 ± 0.1 [0.800 ± 0.005]	12.5 ± 0.1 [0.565 ± 0.005]
D—Diameter (Note 1)	12.5 ± 0.2 [0.500 ± 0.010]	9.0 ± 0.1 [0.350 ± 0.007]	6.0 ± 0.1 [0.250 ± 0.005]	4.0 ± 0.1 [0.160 ± 0.003]	2.5 ± 0.1 [0.113 ± 0.002]
R—Radius of fillet, min	10 [0.375]	8 [0.25]	6 [0.188]	4 [0.156]	2 [0.094]
A—Length of reduced section, min (Note 2)	75 [3.0]	54 [2.0]	36 [1.4]	24 [1.0]	20 [0.75]

Table 2.1 Standard dimensions of cylindrical tensile specimen [7].

2-9 IMPACT TESTING

Toughness of a material is defined as the ability of the material to absorb energy. It is generally characterized by the area under the stress-strain curve for a smooth (un-notched) tension specimen loaded slowly to fracture. Notch toughness of a material is defined as the ability of the material to absorb energy during the impact testing in the presence of notch.

The notch- toughness characteristics of low and intermediate strength steels is described by the ductile to brittle transition behavior as test temperature increases. The most widely used specimen for characterizing the ductile to brittle transition behavior is the Charpy V-notch specimen which is described in ASTM E 23 [8].

The dimensions of standard Charpy V-notch specimen is 55mm*10mm*10mm with a notch in the centre of 45^o angle and about 2mm deep.

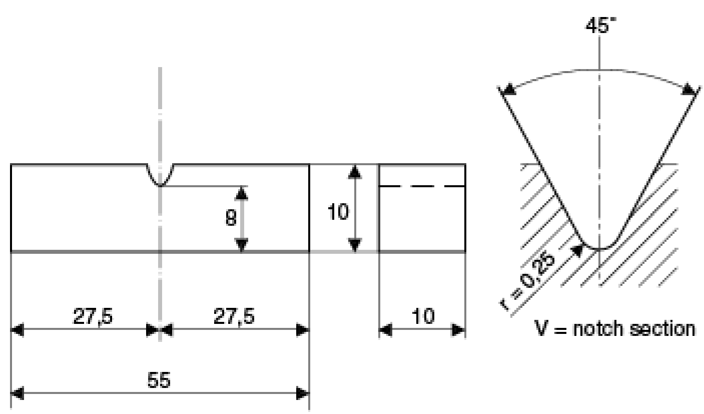

Fig. 2.6 Charpy V- notch specimen with standard dimensions.

2-10 HARDNESS

Hardness of a material is defined as the resistance to permanent indentation or deformation when in contact with an indenter under load. Hardness test is generally done by pressing an indenter of known geometry and mechanical properties into the test material. The hardness of a material is generally quantified by directly or indirectly by the contact pressure involved in deforming the test specimen. There are many types of indenter such as spherical (Brinell test), pyramidal (Vickers and Knoop test), or conical (Rockwell test).

Hardness tests are not only limited to metals but also it covers vast range of materials including polymers, elastomers, thin films, semi-conductors, and ceramics. For metals, hardness is directly proportional to the uniaxial yield stress at the strain imposed by indentation [9]. But this is not applicable for polymers, since their yield is not properly defined.

CHAPTER

THREE

EXPERIMENTAL TECHNIQUES

3-1 MATERIAL SELECTION

The material used in turbine shafts is determined mainly under Class D of ASTM standard A668 and the chemical composition and mechanical properties are specified accordingly.

3-1-1 CHEMICAL COMPOSITION

The ASTM Class D steel material should have a composition as given in Table 1.

Sl. No.	Element	Percentage
1	Carbon	0.30-0.45
2	Manganese	0.90
3	Phosphorous	0.04
4	Sulphur	0.04
5	Silicon	0.35

Table 3.1: Chemical Composition of steel specimen.

MECHANICAL PROPERTIES

The following mechanical properties are required to be achieved, as mentioned in ASTM standard. Even though they are achievable on a small prototype sample, achieving the same

T.S. (MPa)	Y.S. (min, MPa)	Impact Value (Joules)	% Elongation	Vickers Hardness (VHN)
515	260	47	24	160-220

properties for the actual size of turbine shaft is complicated due to dynamic working conditions.

Table 3.2: Mechanical Properties of steel specimen

3-2 HEAT TREATMENT

3-2-1 HARDENING

The normalized steel was cut into slabs of suitable size so as to minimize wastage of material and optimize heat treatment of the part. A smaller sample ensures uniform heating up to the core. But conducting experiments on such small sizes at the laboratory scale deviates from the actual practical working conditions of the full sized rotors which experience much more drastic changes in temperature and pressure.

Austenitizing temperature - 860 ^{0}C

Soaking time - 3 hours

Quenching media - Oil

Soaking time is generally calculated as 30min for every 25.4 mm cross-section (1 in.) and extra 2 hours in addition.

3-2-2 TEMPERING

Tempering is a crucial stage of heat treatment with which we can alter the microstructure and hence, the mechanical properties of the sample. A higher tempering temperature signifies that more amount of stress is relieved from the grains and even a much higher temperature can also induce recrystallization and substantial grain growth. Higher the temperature during tempering, softer is the material and lower is the hardness. Decrease in hardness decreases the tensile strength but consequently increases the impact strength. Hence, an optimum tempering temperature should be selected so as to obtain a better combination of these two properties.

Tempering temperature - 580 ^{0}C

Soaking time - 4 hours

Soaking time for tempering is generally calculated as 60 min per 25.4 mm cross section along with 2 hours in addition.

3-3 TENSILE TESTING

A tensile test was conducted on INSTRON 1195 at the tempered samples. Sub-sized specimens were prepared with gauge length 24mm and diameter 6mm. The strain rate was 2 mm/min at a full scale load range of 50 KN. Three samples were tested and data was recorded. The fractured samples were also taken for the fractography study.

3-4 CHARACTERIZATION TECHNIQUES

Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD) were the two characterization techniques carried out during the experimentation. SEM was mainly employed to take highly magnified images of the fracture surfaces of the tensile specimen and of the microstructure of the normalized and tempered sample. The fractographic study of the fractured specimen let us know about the general nature of the sample. The applied accelerating potential was 20 KV and magnifications of X500 and X1000 were reached.

X-Ray Diffraction was done to analyze the phases present in the steel specimen. It also gives an idea about the major crystallographic planes of the elements present in the sample. The angle was progressing at the rate of 2^0/min. The graph obtained was studied using X'pert High Score and PCPDF software and major constituents of the steel sample were found out.

3.5 <u>HARDNESS TESTING</u>

Vicker's Hardness Indenter was used to measure the hardness of the sample. Hardness of the normalized and the tempered sample were measured. In Vicker's indentation technique, a diamond indenter is used to indent the substance. A load of 100gf and a dwell time of 10 sec were set for the measurements and then using the dimensions of the indentation mark (pyramid) we obtained the hardness. The unit is VHN (Vicker's Hardness Number) or VPN (Vicker's Pyramid Number).

3.6 <u>IMPACT TESTING</u>

Charpy Impact machine was used to measure the impact strength of the steel sample. A sample of dimensions 55 X 10 X 10 mm^3 was made and provided with a v-notch of depth 2mm and a root angle of 45^0. A 30 kg hammer was used and three samples were tested. The readings were obtained in units kg m, but were converted to Joules as per the standards.

$$1 \text{ kg m} = 9.81 \text{ N m} = 9.81 \text{ Joules}$$

CHAPTER

FOUR

RESULTS AND DISCUSSION

The experiments conducted were followed by data analysis and explanation. The result analysis can be broadly classified into two parts, first being the mechanical testing. It comprises of the results obtained from tensile test and impact toughness test. It also includes the hardness data obtained from Vicker's Hardness test. The other half consists of the characterization of the sample which includes analysis of the images obtained from SEM and of the diffraction pattern obtained from XRD.

4-1 TENSILE TEST

Following table shows the test results obtained from tensile testing of the sample using INSTRON 1195.

Specimen Number	Ultimate tensile strength (MPa)	Yield Strength (MPa)	%Elongation	Youngs' Modulus (MPa)
1	619.2	275.6	42.17	10170
2	600.1	252.0	39.08	9817
3	595.2	258.3	40.25	9360
Mean	604.8	262.0	40.50	9783

Table 4.1 Tensile test data

All the specimens were tested at a strain rate of 2 mm/min. The ultimate tensile strength strongly depends on the strain rate and the temperature at which the test is conducted.

4-2 IMPACT TESTING

Weight of Hammer = 30 kg

Specimen dimensions = 55x10x10 mm^3

v-notch depth = 2 mm

Conversion factor = 9.81

Specimen Number	Energy absorbed (kg m)	Impact Strength (x 9.81) (Joules)
1	5.8	56.9
2	6.5	63.8
3	6.4	62.8
Mean	6.23	61.2

Table 4.2 Impact test data

The stress concentration in Charpy v-notch is more than that will be in a u-notch, hence there may be differences in readings for different laboratory measurements. Also weight of the hammer has a significant effect on the impact strength.

The impact strength of a material can be altered by changing the heat treatment parameters. But impact toughness is inversely proportional to tensile strength. Hence, proper care has to be taken while altering the heat treating parameters in order to obtain a balance between strength and toughness.

4-3 HARDNESS

Load = 100 gf

Dwell time = 10 sec

Sample 1 (As-received steel)

No. of Observation	**Hardness (VPN)**
1	203.1
2	238.9
3	242.0
4	237.0
Mean	230.2

Sample 2 (Hardened/Tempered)

No. of Observation	**Hardness (VPN)**
1	251.6
2	245.1
3	295.6
4	305.8
Mean	274.5

Table 4.3

Hardness test data

It is evident from the above data that hardness increased after hardening and tempering of the steel sample. Average hardness of the tempered steel obtained is 274.5 VPN.

4-4 COMPARISON OF ACTUAL DATA WITH TARGET VALUES

	U.T.S. (MPa)	Y.S. (MPa)	Elongation (%)	Impact Value (Joules)	Hardness (VPN)
Actual	604.8	262.0	40.5	61.2	274.5
Target	515.0	260.0	24.0	47.0	160-220

Table 4.4 Comparison between actual and target values

As is evident from the above comparison, all the mechanical properties obtained are better than that required by the ASTM standards. Properties other than yield strength have large tolerances, but yield strength obtained falls very close to that targeted. Hence, changes can be made in the heat treatment to improve the yield strength of the material.

A decrease in the tempering temperature will increase the yield strength of the steel specimen. This is so because a lower tempering temperature will enable the material to retain more hardness and dislocation density, thus the material will have a higher yield strength. But consequently, the impact strength of the specimen will decrease, as impact value is inversely proportional to tensile properties. Since, there is a higher tolerance available for impact value, tempering temperature can be lowered to 550-560 ^{0}C in comparison to 580 ^{0}C used in the present investigation.

4-5 <u>SCANNING ELECTRON MICROSCOPE</u>

Highly magnified images of the fracture surface were taken after the tensile testing was done. Following are the images obtained:

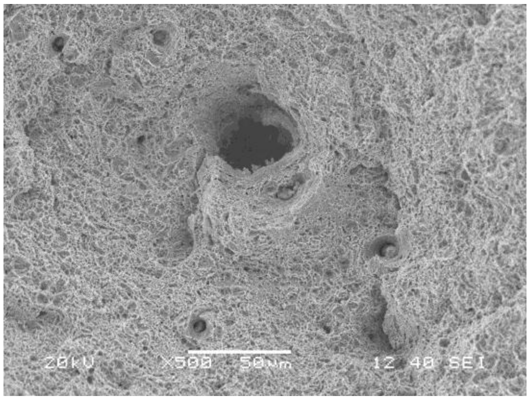

Fig. 4.1 SEM image of the fracture surface

A cup and cone type of fracture was observed during tensile testing. When observed under scanning electron microscope, dimpled fracture was clearly observed, which means that significant amount of plastic deformation has taken place. Absence of any cleavage planes or facets implies that no brittle fracture has occurred.

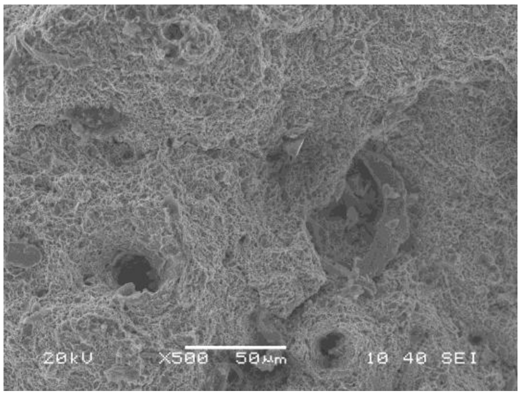

Fig. 4.2 SEM image showing dimpled fracture

The above fig. 4.2 shows the presence of dimples at the fracture surface. Dimpled surface represents ductile fracture of the substance.

4-6 XRD ANALYSIS

XRD pattern of as-forged/normalized was studied and the graph obtained is as follows:

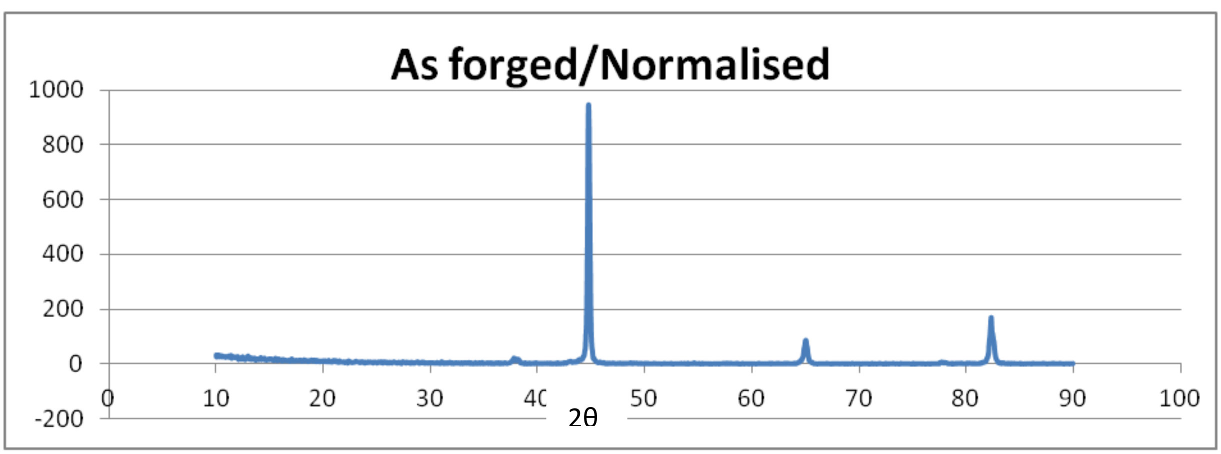

Fig 4.3 XRD pattern for as-forged/normalized sample

The graph showed a major peak at 44.5^0 which represents Fe [110] plane. Other minor peaks were also recognized for Fe, as Fe is the main constituent of the steel sample. Certain peaks were recognized for C and Mn as well.

The XRD pattern for hardened/tempered steel was also studied and graph obtained was as follows:

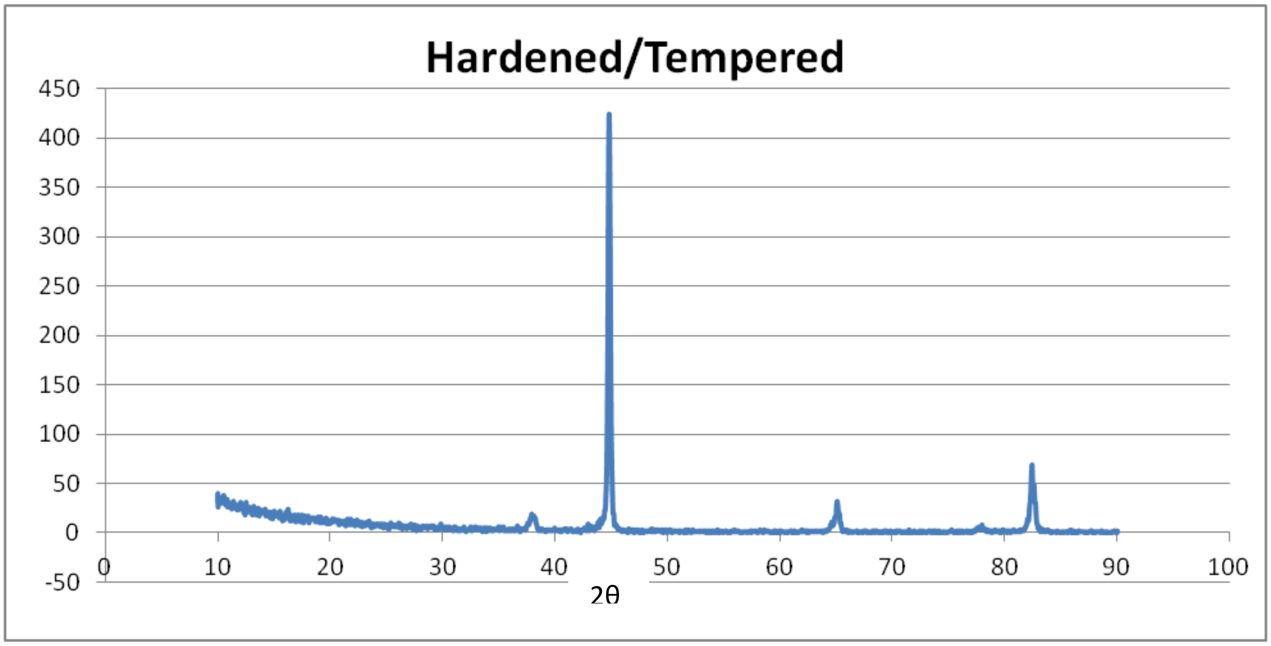

Fig. 4.4 XRD pattern for hardened/tempered sample

Similar peaks were also obtained for hardened/tempered sample which signifies that there is no second phase formation due to the heat treatment. There is no carbide formation which shows the absence of any allowing elements.

Hence, the strength observed the given prototype is mainly due to solid solution strengthening (interstitial).

The steel is a plain carbon steel with minute quantities of Si, Mn, P, and S as regular impurities, having no major impact on the physical properties of the sample.

CHAPTER

FIVE

CONCLUSION

As required by the ASTM standards, the mechanical properties required for turbine shaft applications were satisfactorily achieved on the prototype provided. However, validity of such properties is not certain for actual size applications of the turbine shaft which in practice undergoes a dynamic environment.

The soaking time normally used in the laboratory scale was 2-3 hours keeping in sight the dimensions of the sample (1-2 in.). But turbine shafts have a much larger cross-section and hence should be given more holding time at high temperatures for homogenous heating. The soaking time for actual practice during tempering may vary from 40-50 hours (~1200mm cross-section) and 20-25 hours during hardening keeping the heating temperatures in both the processes, i.e. 580 ^{0}C in tempering and 860 ^{0}C in hardening.

The yield stress of 262 MPa was observed to be almost equal to the required value of 260 MPa. This can be improved by decreasing the tempering temperature by 20-30 ^{0}C. This will reduce the impact toughness but will keep it within the required values.

Hence, for a further study under this topic, one can alter the tempering temperatures to alter the mechanical properties in order to obtain a better combination of these properties. Even though an optimum combination of impact and tensile strength was achieved in the present experimentation, still endeavors can be made to improve the properties and apply it successfully for turbine shaft applications.

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APPENDIX-I

Chemical Composition of material under ASTM A668

Element	Grade X1	Grade X2	Grade X3	Grade X4	Grade X5	Grade X6
Carbon	0.30	0.45	0.40	0.45	0.45	0.40
Manganese	0.90	0.90	0.85	1.10	0.90	0.90
Phosphorous	0.04	0.04	0.025	0.025	0.025	0.015
Sulfur	0.04	0.04	0.025	0.025	0.025	0.015
Silicon	0.35	0.35	0.35	0.35	0.35	0.35
Nickel	. . .	. . .	3.75	. . .	2.00	2.50
Chromium	. . .	. . .	. . .	1.10	1.00	1.25
Molybdenum	. . .	. . .	. . .	0.25	0.30	0.60
Vanadium	. . .	. . .	. . .	. . .	. . .	0.20

TABLE X2.2 Class/Grade Guide

Class	Brinell Hardness	Applicable Grades
Carbon Steel		
A	183 max	X1
B	120–174	X1
C	137–183	X1, X2
D	149–207	X1, X2
E	174–217	X2
F	187–235	X2
Alloy Steel		
G	163–207	X3, X4
H	187–235	X3, X4
J	197–255	X3, X4, X5
K	212–269	X3, X5
L	255–321	X4, X5
M	293–352	X5, X6
N	331–401	X6

Mechanical Properties of material under ASTM A668

Class	Size, in. [mm]		Tensile Strength, min		Yield Point, Yield Strength 0.2 % Offset, min		Elongation in 2 in. or 50 mm, min, %	Reduction of Area, min, %	Brinell Hardness
	Over	Not Over	psi	MPa	psi	MPa			
Carbon Steel									
A (AH) (Untreated)	...	20 [500]	47 000	325	...	...	...	...	183 max
B (BH) (Annealed, or normalized, or normalized and tempered)	...	20 [500]	60 000	415	30 000	205	24	36	120–174
C (CH) (Annealed, or normalized, or normalized and tempered)	...	12 [300]	66 000	455	33 000	230	23	36	137–183
	12 [300]	20 [500]	66 000	455	33 000	230	22	34	137–183
D (DH) (Normalized, annealed, or normalized and tempered)	...	8 [200]	75 000	515	37 500	260	24	40	149–207
	8 [200]	12 [300]	75 000	515	37 500	260	22	35	149–207
	12 [300]	20 [500]	75 000	515	37 500	260	20	32	149–207
	20 [500]		75 000	515	37 500	260	19	30	149–207
E (EH) (Normalized and tempered or double-normalized and tempered)	...	8 [200]	85 000	585	44 000	305	25	40	174–217
	8 [200]	12 [300]	83 000	570	43 000	295	23	37	174–217
	12 [300]	20 [500]	83 000	570	43 000	295	22	35	174–217
F (FH) (Quenched and tempered, or normalized, quenched and tempered)	...	4 [100]	90 000	620	55 000	380	20	39	187–235
	4 [100]	7 [175]	85 000	585	50 000	345	20	39	174–217
	7 [175]	10 [254]	85 000	585	50 000	345	19	37	174–217
	10 [250]	20 [500]	82 000	565	48 000	330	19	36	174–217
Alloy Steel									
G (GH) (Annealed, or normalized, or normalized and tempered)	...	12 [300]	80 000	550	50 000	345	24	40	163–207
	12 [300]	20 [500]	80 000	550	50 000	345	22	38	163–207
H (HH) (Normalized and tempered)	...	7 [175]	90 000	620	60 000	415	22	44	187–235
	7 [175]	10 [250]	90 000	620	58 000	400	21	42	187–235
	10 [250]	20 [500]	90 000	620	58 000	400	18	40	187–235
J (JH) (Normalized and tempered, or normalized, quenched, and tempered)	...	7 [175]	95 000	655	70 000	485	20	50	197–255
	7 [175]	10 [250]	90 000	620	65 000	450	20	50	187–235
	10 [250]	20 [500]	90 000	620	65 000	450	18	48	207–255
K (KH) (Normalized, quenched, and tempered)	...	7 [178]	105 000	725	80 000	550	20	50	212–269
	7 [175]	10 [250]	100 000	690	75 000	515	19	50	207–269
	10 [250]	20 [500]	100 000	690	75 000	515	18	48	207–269
L (LH) (Normalized, quenched, and tempered)	...	4 [100]	125 000	860	105 000	725	16	50	255–321
	4 [100]	7 [175]	115 000	795	95 000	655	16	45	235–302
	7 [175]	10 [250]	110 000	760	85 000	585	16	45	223–293
	10 [250]	20 [500]	110 000	760	85 000	585	14	40	223–293
M (MH) (Normalized, quenched, and tempered)	...	4 [100]	145 000	1000	120 000	825	15	45	293–352
	4 [100]	7 [175]	140 000	965	115 000	790	14	40	285–341
	7 [178]	10 [254]	135 000	930	110 000	758	13	40	269–331
	10 [250]	20 [500]	135 000	930	110 000	758	12	38	269–341
N (NH) (Normalized, quenched, and tempered)	...	4 [100]	170 000	1175	140 000	965	13	40	331–401
	4 [100]	7 [175]	165 000	1140	135 000	930	12	35	331–401
	7 [175]	10 [250]	160 000	1100	130 000	900	11	35	321–388
	10 [250]	20 [500]	160 000	1100	130 000	900	11	35	321–402